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CYCLE ANALYSIS OF AIRCRAFT TURBINE ENGINES

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AN APPROACH TO THE LIFE-CYCLE ANALYSIS OF AIRCRAFT TURBINE ENGINES

J. R. Nelson

A Rand Note
prepared for the
United States Air Force

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See Reverse Side

A paper prepared for the AGARD/NATO Lecture Series,
"The Application of Design to Cost and Life-Cycle
Cost to Aircraft Engines," scheduled for May 1980.
A methodology is described for life-cycle analysis of
aircraft turbine engines from historical data. The
methodology enables the weapon-system planner to acquire
early visibility of cost magnitudes, proportions, and
trends associated with a new military engine's life
cycle, and to identify "drivers" that increase cost
and can lower capability. The methodology is applied
at the engine subsystem and aircraft system levels
for a military fighter aircraft to demonstrate that
decisions about engine performance/schedule/cost must
be made at the system level. Commercial considerations
are discussed, as is limited historical experience in
engine monitoring, an approach to obtaining the nec-
essary information and procedures for performance and
cost feedback to the engine designer. This Note pre-
sents portions of previously published Rand work on
life-cycle analysis of aircraft turbine engines and
engine monitoring systems, together with some recent
unpublished work applying the earlier efforts at the
aircraft system level.   (Author)

PREFACE

This Note presents portions of previously published Rand work concerning the life-cycle analysis of aircraft turbine engines and engine monitoring systems, together with some recent unpublished work applying the earlier efforts at the aircraft system level.

The previously published material can be found in Rand Reports R-2103-AF, *Life-Cycle Analysis of Aircraft Turbine Engines*, by J. R. Nelson, November 1977, and R-2391-AF, *Aircraft Turbine Engine Monitoring Experience: Implications for the F100 Engine Diagnostic System Program*, by J. L. Birkler and J. R. Nelson, April 1979.

The material assembled here will be presented as a paper in the AGARD/NATO Lecture Series "The Application of Design to Cost and Life-Cycle Cost to Aircraft Engines," scheduled for May 1980. The work was done under the Project AIR FORCE research project "Methods and Applications of Life-Cycle Analysis for Air Force Systems."

SUMMARY

This paper presents the results of a study that describes a methodology derived from historical data for life-cycle analysis of aircraft turbine engines and applies that methodology at the engine subsystem and aircraft system levels. The methodology enables the weapon-system planner to acquire early visibility of cost magnitudes, proportions, and trends associated with a new engine's life cycle, and to identify "drivers" that increase cost and can lower capability. The procedure followed was to develop a theoretical framework for each phase of the life cycle; collect and analyze data for each phase; develop parametric cost-estimating relationships (CERs) for each phase; use the CERs in examples to ascertain behavior and obtain insights into cost magnitudes, proportions, and trends, and to identify cost-drivers and their effects; and examine commercial experience for cost data and operational and maintenance practices.

The methodology is applied at the engine subsystem and aircraft system levels for a military fighter aircraft to demonstrate that decisions about engine performance/schedule/cost must be made at the system level. Commercial considerations are also discussed, as is some limited historical experience on engine monitoring--an approach to obtaining the necessary information and procedures for performance and cost feedback to the operational user, military planner, and engine designer.

The study was prompted by the steadily escalating costs of acquiring and owning turbine engines for both military and commercial users. Most of the causes are readily apparent. Demands for higher overall quality--meaning performance, primarily, for the military--have resulted in larger engines that produce greater thrust, run hotter, are costlier to maintain, and entail higher basic engine prices. Material costs associated with engine price have also risen rapidly in the recent past; over the long term, however, labor costs, primarily in the manufacturing sector, have risen proportionately more so.

The chief problem confronting this study, as it has confronted past researchers, is the lack of disaggregated, homogeneous, longitudinal

ownership data that are specific to particular engine types, notably at the base and depot level. The collection of such data will be necessary for perfecting the methodology, which weapon-system planners can then use to calculate the costs and benefits of a proposed engine for a new aircraft in the early stages of planning and selection.

For a new military engine (acquired and owned under conditions similar to those of previous engines constituting the data base) that will have an operational lifespan of 15 years, the findings indicate that:

o   Engine ownership costs are significantly larger than and different from those found in previously published studies. For instance, engine depot and base maintenance costs, not including fuel and attrition, can exceed engine acquisition costs. This finding is true for current fighter and transport engines.

o   Depot costs alone can exceed procurement costs.

o   Component improvement programs (CIP) conducted during the operational life of an engine can cost as much as it did to develop the engine to its initial model qualification.

o   If component improvement and whole spare engine procurement are considered ownership costs, then ownership currently constitutes at least two-thirds of total engine life-cycle cost. This is true for current supersonic fighter and subsonic transport/bomber engines.

o   Satisfying results, in terms of statistical quality, theoretical behavior, and experience from past programs, were obtained from modeling performance/schedule/cost relationships for the development and production of military engines; mixed but promising results were obtained in modeling ownership costs for military engines.

o   Application of the models derived in this study indicates that there is a continuing trend toward higher ownership costs, measured in both absolute dollars and as a percentage of total life-cycle costs. Increasing depot cost is the primary reason for this trend. The production cost of the engine (and its

parts) is a contributor to depot and base support costs, but
so are ownership policies.

o   The engine maturation process must be more fully understood
     if improved analytical results are to be obtained and applied
     to new engine selection. It takes an engine a long time to
     mature (commercial experience indicates five to seven years).
     Consequently, average ownership costs are significantly higher
     during that period than mature engine steady-state costs in
     terms of dollars per flying hour, the yardstick most commonly
     used. It is believed that engine monitoring systems will
     assist in providing designers with the necessary information
     in the future.

o   Finally, and most importantly, the selection of engine design
     parameters and the appropriate engine technology level and
     performance/reliability criteria must be made at the aircraft
     system level.

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SYMBOLS

ATBO = Average time between overhaul, hours

CAB = Civil Aeronautics Board

CIP = Component improvement program cost, millions of 1975 dollars

CPUSP = Current production unit selling price, thousands of 1975 dollars

DMQTC = Development cost to MQT, millions of 1975 dollars

DEVTIME = Development time from start to MQT, calendar quarters

EFH = Engine flying hour

EFHC = Engine flying hour consumed by operating fleet

EFHR = Engine flying hour restored to fleet by depot maintenance

IR&D = Independent Research and Development

KPRATE = Average production rate, 1000 engines/quarter*

KPUSP = 1000th unit production cost, millions of 1975 dollars

LCC = Life-cycle cost

MACH = Maximum flight envelope Mach number (measure of speed related to speed of sound)

MCDUM = Military-commercial dummy (1 = commercial, 0 = military)

MFRDUM = Manufacturer dummy (1 = Pratt & Whitney, 0 = others)

MQT = Model Qualification Test

MQTQTR = Man-rated 150-hr Model Qualification Test date, calender quarters (October 1942 = 1)

MQTY = Total quantity produced, millions of units

MTBO = Maximum time between overhaul, hours

MVOLUME = Engine volume (maximum diameter and length, cu. in./10^6)

OPSPAN = Time since operational use began, quarters

PRQTYC = Production quantity cumulative cost at quantity purchased, millions of 1975 dollars

QMAX = Maximum dynamic pressure in flight envelope, lb/ft^2

QTY = Quantity of production engines procured

RDT&E = Research, development, test, and evaluation

RMS = Resource Management System

_____

*Several variables are expressed in what appear to be unusual units in order to obtain significant figures in the computer output for various equations.

SFCMIL = Specific fuel consumption at military thrust, sea-level static (SLS), lb/hr/lb thrust

TEMP = Maximum turbine inlet temperature °R

THRMAX = Maximum thrust (with afterburner if afterburner configuration), SLS, lb

TOA = Time of arrival

TOA26 = Time of arrival of demonstrated performance obtained from model derived using 26 military turbojet and turbofan engines, calendar quarters

TOA37 = Time of arrival of demonstrated performance obtained from model derived using 26 military military and 11 commercial turbojet and turbofan engines, calendar quarters

ΔTOA26 = TOA26-MQTQTR, calendar quarters

TDC = Total development cost including MQT and product improvement, millions of 1975 dollars

TOTPRS = Pressure term (product of QMAX × pressure ratio), lb/ft^2

WGT = Weight of engine at configuration of interest, lb

I. INTRODUCTION

Over the past several decades, the U.S. Department of Defense has placed increasing emphasis on understanding and assessing acquisition strategies and cost considerations in the development and procurement of new weapon systems. In the present era of budget constraints, and with an increasing share of the military budget devoted to operating and supporting forces in being, it has become even more important to be able to measure the contribution of both new and existing weapon systems to the overall defense posture in a *life-cycle* context--that is, their benefits relative to their total life-cycle costs.

Attention has recently focused on attempts to understand and predict total life-cycle costs for new weapon systems and important subsystems, including aircraft turbine engines. In this context, aggregation of costs is not enough; the key is to understand total life-cycle costs in terms of magnitude, distribution among cost elements, and trends over time relative to the benefits to be obtained. Such cost elements include not only those of acquisition (development and procurement) of a new weapon system, but also all the costs of operating and supporting the system in the field during its inventory lifetime. The latter costs, for both existing and proposed weapon systems, must be more clearly understood to make effective trade-offs during new developments and procurements.

OBJECTIVE OF THE STUDY

The study of the life-cycle analysis of aircraft turbine engines has a two-fold objective: (1) to develop a methodology for assessing life-cycle benefits and costs; and (2) to apply that methodology to improve understanding of policy options for engine acquisition and ownership.

The problem addressed is the weapon-system planner's lack of detailed information and a methodology to enable him to make early decisions concerning the selection of a new engine for a new weapon system, all within a life-cycle context. Accordingly, this paper presents

information on and a methodology for life-cycle analysis, derived from the study of historical data on military and commercial engines, to provide a weapon-system planner with an early analytical perspective. This methodology, when backed up with appropriate data collection, should equip the weapon-system planner with improved early *visibility* of the magnitudes, proportions, and trends of costs associated with the various phases of an engine's life cycle. He should then be able to identify influential parameters that drive costs and exert leverages between life-cycle phases, and thus be able to assess trade-offs among quality, schedule, and cost in the search for policies appropriate to the various phases of a new engine's life cycle.

The major concern in this study, then, is to illuminate the entire life-cycle process for military aircraft turbine engines in terms of overall benefits and costs and their interactions. Commercial experience is also investigated to identify practices that the military might profitably adopt.

The procedure followed was to: (1) develop a theoretical framework for each phase of the life-cycle, one feature of which was use of a technique for assessing the state-of-the-art advance represented by a new engine; (2) collect and analyze data for each phase; (3) develop and test parametric cost-estimating relationships (CERs) for each phase; (4) use the CERs in examples to ascertain behavior and obtain insights into cost magnitudes, proportions, and trends and to identify cost-drivers and their effects; and (5) examine commercial practice for cost data and operational and maintenance practices.

BACKGROUND

Aircraft turbine engines are a particularly promising subject for study because: (1) they are extremely important in weapon-system applications; (2) they are felt to be the pacing subsystem in aircraft weapon-system development; (3) they represent a large inventory and budgetary expense; (4) their 40-year history of continuing technological improvement furnishes a sizable (though fragmentary) data base for analysis; and (5) they could provide insights, from a subsystem viewpoint, across the life-cycle spectrum, that may be readily applicable

to the weapon-system level. The subject also has an immediate practical urgency: Engines are a topic of considerable interest today because of problems arising in the operational inventory with aircraft grounded owing to engine-related problems.

RESULTS OF PREVIOUS STUDIES

Many past studies have attempted to shed light on the engine life-cycle process, and current studies within the military community tend to emphasize life-cycle cost estimates. The central question is, How much does it cost to acquire and own a new military engine over its life cycle? No previous study has been able to answer that question fully. It is obvious that the two major problems are: (1) accurately measuring what has already taken place; and (2) using such information to predict the future.

The most recent studies examined have been more qualitative than quantitative, or for the most part have addressed only a portion of the life cycle. (See, for example, Ref. 1.) Some previous studies have attempted to quantify operating and support costs and total life-cycle costs for specific engines, but no study to date has clearly and consistently defined *all* of the relevant cost elements and obtained their associated actual costs for any ongoing engine program. Furthermore, no methodology has been provided for predicting costs for new engines over the entire life cycle. The lack of data is the persistent obstacle. For existing engines in the USAF inventory, studies of operating and support costs have been performed with cross-sectional data; in many cases, they cover only a single fiscal year or even less. For a new engine, the procedure has been to select a closely similar existing engine and use modified cross-sectional data from that engine's current experience (usually at steady-state conditions) in an attempt to project operating costs over the proposed engine's entire life cycle. The combined lack of disaggregated, homogeneous, longitudinal data and of a reliable methodology for projecting detailed cost estimates over a new engine's life cycle have frustrated attempts to estimate life-cycle costs. Furthermore, none of these previous studies have attempted quantitative calculations of the effect of state-of-the-art advances on life-cycle costs.

All these difficulties have led earlier studies to the erroneous conclusion that engine base and depot maintenance costs are a relatively minor fraction of total life-cycle costs for an engine--as little as one-tenth to one-fifth, with the range being affected by whether or not fuel consumption attributed to a mission was considered within the total cost estimate. These earlier studies suffered from the difficulty of defining the cost elements associated with each of the phases of the life cycle, and ascertaining whether these cost elements were consistent over time and whether all relevant cost elements were indeed included; their results further depended heavily on the data sources and assumptions they employed. For instance, hourly labor rates used to estimate base and depot labor costs will vary markedly, depending on the extent to which the direct labor cost is burdened by applying appropriate overhead charges. Many studies have omitted significant portions of the direct labor-hour cost burden. Another difficulty lies in assuming that cross-sectional operating and support costs are average costs sustained over the entire life cycle. The cross-section is likely to have been taken either during the steady state of a mature engine or during its immature dynamic state; since neither state is "average," a cross-section can seriously distort the estimate either up or down. The impact of advanced technology is to bias cost estimates on the low side.[*]

Previous studies have estimated engine ownership costs in a range of $20 to $200 per engine flying hour. Recent data obtained for this study indicate that costs can be as much as an order of magnitude higher (even after adjusting for inflation) for the newer, high-technology engines for comparable mission objectives. It is possible that some previous cost figures were valid for earlier weapon systems at specific points in time, but current systems are tending toward considerably higher average operating and support costs, and future systems threaten to be even more costly if no actions are taken to change the direction of this trend. Relying on older engine steady-state costs to directly reflect new engine average costs over a 15-year time span can seriously underestimate future costs.

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[*]Defense programs are not the only examples of this problem. See Ref. 2 for examples in the energy sector.

II. LIFE-CYCLE ANALYSIS

The life-cycle analysis of a new weapon system must be based on an understanding of all phases of the life-cycle process, both separately and as they interact. Phases include concept formulation, validation, development, procurement, deployment, operational use, and disposal. The life-cycle process extends over two to three decades, depending upon the quality originally sought and the quality obtained, the length of time spent in each phase, and the importance of the system in the inventory. The creation of a weapon system involves many organizations within the Government, military service, and private industry. While life-cycle analysis must be sensitive to institutional practices, the central concern of this study is to develop a methodology that can be applied to benefit/cost trade-offs at the subsystem and system level.

DEFINITIONS AND QUANTITATIVE MEASUREMENT OF BENEFITS AND COSTS

It is often extremely difficult to evaluate quantitatively the benefits to be gained from a new weapon system. For example, the new system may incorporate a technical characteristic that appears to provide a marginal improvement at best over a previous system, but in reality creates a significant combat advantage--but how is that advantage to be measured? In the commercial arena, the bottom line is profit earned for the service provided (where safety is one implied part of service), but it is far from easy to assign a dollar-equivalent to the benefits a weapon system produces in a wartime environment. In attempting benefit and cost assessments for engines, it must also be recognized that analysis at the subsystem level must ultimately be related back to the system; engine output must be measured in terms of its contribution to the weapon system. The true measures are the engine's impact on weapon-system availability and utilization, mission reliability, effectiveness, mobility, and inventory life. It is the task of the weapon-system planner to transform the output measures dealt with in this study into their ultimate value to the system; the

methodology presented here should enable him to do so with more confidence than has heretofore been possible.

DEFINING BENEFIT MEASURES FOR AIRCRAFT TURBINE ENGINES

The aircraft turbine engine has been characterized as one of the highly significant inventions of the twentieth century. Certainly, no one can deny the tremendous importance of the changes its military and commercial applications have wrought on our history and the way we live. But everything comes with a price tag. It has been said, somewhat wryly, that the only trouble with a turbine engine is that it weighs something, it gulps fuel, it takes up space, it creates drag, and it breaks now and then. Like all other inventions, it has its benefits, and it has its costs.

Benefit measures for an engine hinge on its design, how it is used, and how it affects weapon-system quality. Quality is an extremely complex measure that defies absolute quantification in a military context. For an engine, it embraces the sum of the characteristics it is to contribute to a new weapon system (performance, durability, reliability, maintainability, safety), just as life-cycle cost is the sum of all cost elements. However, military quality is partly a subjective matter, more difficult to assess than cost. How much is an extra 50 miles per hour worth to a fighter aircraft? What is it worth to have the aircraft available more frequently? In the weapon-system context, it is possible-- and necessary--to arrive at rational dollar figures for the answers, but subjective judgment will always enter the calculations.

In a life-cycle analysis, we seek to clarify, at least in part, the trade-offs among product quality, schedule, and total cost. When one characteristic of an engine is changed, other characteristics are affected. *Since quality is a combination of many things, it is not certain that an improvement in one characteristic of quality necessarily leads to an overall improvement in quality for the end use desired.* For instance, if performance is increased to the detriment of reliability, it is not clear that overall quality is improved if a higher performance aircraft is less available to perform its mission. In this study, quality is considered closely synonymous with performance in a military

context, and engine performance characteristics will be related to the state of the art to assess schedule and cost impacts in selecting a new engine.

For military systems, quality has primarily meant performance, with other characteristics considered secondary. The goal commonly has been to obtain thrust at a minimum fuel consumption, weight, and installed volume, but other characteristics should be considered. (Commercial practice emphasizes safety, reliability, and cost.) Durability and reliability are so closely related that they are somewhat difficult to distinguish; but durability can be related to design life—the engine's continuing ability to perform the mission in the aircraft during its inventory lifetime. This may entail consideration of several system output measures: flying hours, sorties, takeoffs and landings, engine cycles (throttle movement), and calendar time. Reliability can be expressed as the engine's ability to be ready to go on any given mission and to perform it successfully. Measures of interest are engine removal rates, mission aborts, and time between scheduled base maintenance and depot repair visits. Maintainability is the ease with which the aircraft/engine combination can be maintained in the field. Safety can include design features that may appear to detract from performance—for example, designing engine casings so blades cannot go through them if they separate from the rotor. Such a feature increases engine weight but reduces the chance of substantial airframe damage. Environmental impacts include noise and smoke, which can be reduced at some penalty to engine performance.

The most widely used output measure of ownership cost for a given engine is *cost per engine flying hour*. In the future, however, other measures may become more relevant. With the advent of the high cost of fuel, flying training may be accomplished in fewer flying hours. But pilots can make fuller use of these flying hours so as not to cut down on critical portions of their training. Thus, in the future, flying hours may decrease, but not the number of sorties, takeoffs and landings, and engine cycles; if so, cost per flying hour may not be an appropriate measure. The cost of maintaining the engine inventory may not decrease even though there is a decrease in flying hours and fuel

cost. This is especially true if maintenance is staffed to handle peak workloads in wartime. Another measure is calendar time. The longer an engine is out in the field without major depot rework, the more opportunity it has to undergo corrosive and secondary damage. When it does finally return to the depot, the damage may be more extensive than might be expected on the basis of flying hours alone.

Although this study will primarily use *engine performance* characteristics to relate to state-of-the-art and life-cycle costs, and the *engine flying hour* as an output measure for ownership costs, future data collection efforts should encompass other benefit measures—notably, sorties, takeoffs and landings, engine throttle executions, and calendar time.

THE AIRCRAFT TURBINE ENGINE LIFE-CYCLE PROCESS

Just as there is a life-cycle process at the weapon-system level, there is also such a process at the subsystem level. The subsystems of an aircraft weapon system include the airframe, engine, avionics, armament, and support equipment. It must be clearly understood that optimizing engine quality/schedule/cost does not necessarily do the same for the *system*. In the final analysis, decisions must be made *at the system level*; however, understanding the subsystem level can aid in understanding the system level.

The life-cycle process of an aircraft turbine engine encompasses the entire spectrum of research, development, procurement, and ownership. The requirement for a new engine is tightly interwoven with the requirement for a new weapon system. Figure 1 depicts this process, which is iterative during the design phase and makes use of feedback from operational experience as well as expectations from new technology. The characteristics of the weapon system required to satisfy the military need combine airframe, engine, avionics, armament, and support subsystems technology; the particular selection of characteristics is based on technical considerations tempered by operational experience.

This study focuses on development, procurement, and ownership; it does not explicitly consider basic research or exploratory and advanced development, the reduction of new knowledge to hardware, or the testing
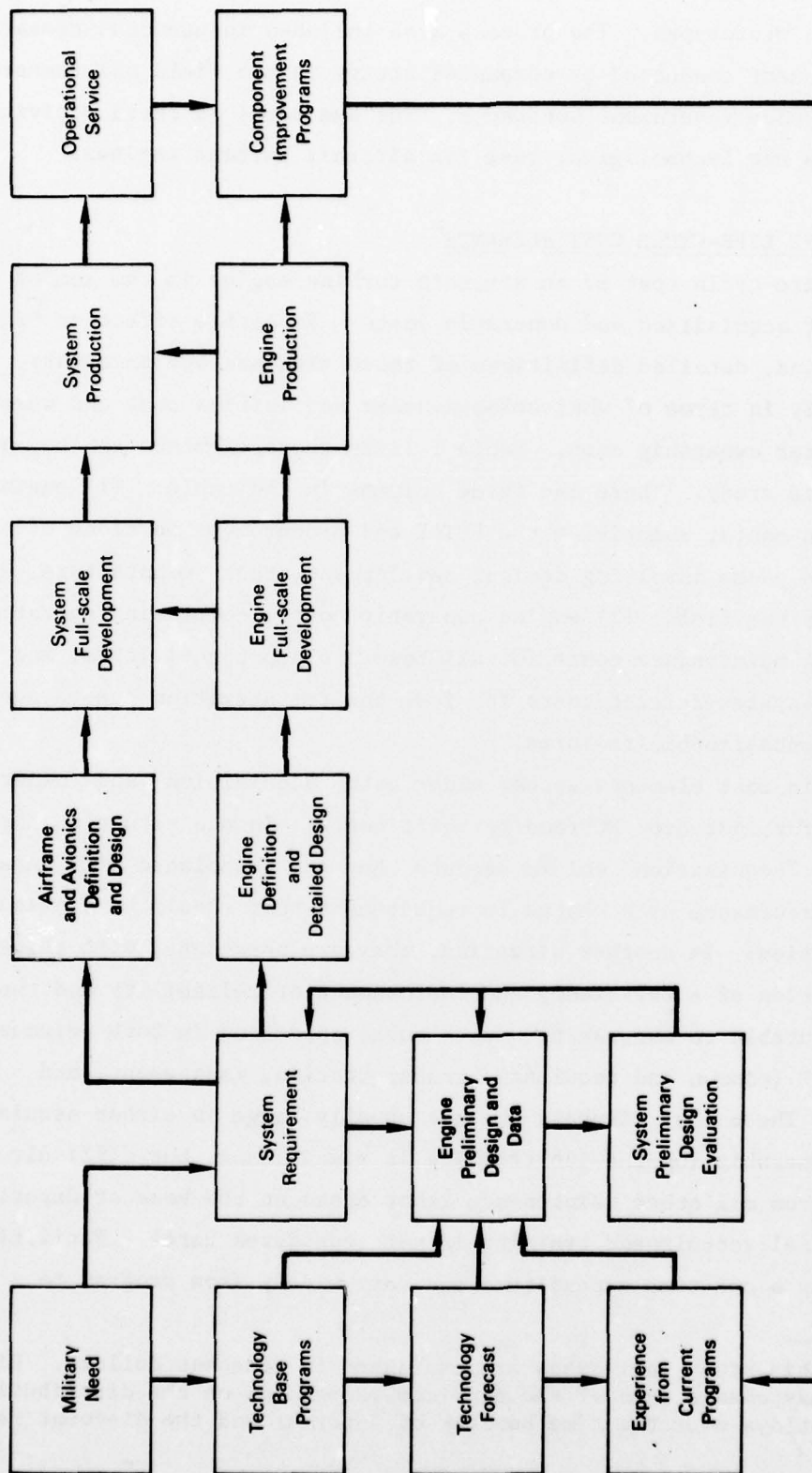
Fig. 1—Aircraft turbine engine design and development process

of advanced prototypes. The process also includes independent research and development conducted by companies active in the field and research conducted under government contracts. The sum total of these activities constitutes the technological base for aircraft turbine engines.

DEFINING THE LIFE-CYCLE COST ELEMENTS[*]

The life-cycle cost of an aircraft turbine engine is the sum of all elements of acquisition and ownership costs. To enable effective trade-off decisions, detailed definitions of those elements are necessary, particularly in terms of what belongs under acquisition cost and what belongs under ownership cost. Table 1 lists those elements as they are used in this study. There are three columns in the table: (1) engine acquisition costs, comprising the RDT&E and procurement portions of the acquisition phase involving design, development, test, manufacture, and delivery to the field; (2) engine ownership costs, comprising operating and support maintenance costs for all base and depot activities; and (3) weapon-system-related costs for fuel and for attrition due to accidents and catastrophic failures.

Certain cost elements appear under both "acquisition" and "ownership," as for instance, ECP/mod/retrofit costs. In one situation they are in the "acquisition" column because they are associated with enhancement of performance or a change in requirement that should be attributed to acquisition. In another situation, they are associated with changes for correction of a deficiency and improvement of reliability and thus are attributable to ownership. Other costs appearing in both columns include AGE (common and peculiar), transportation, management, and training. These cost elements are not usually large in either acquisition or ownership (on-the-job training is significant, but difficult to separate from all other maintenance labor costs at the base or depot; also, initial recruitment training is not considered here). Facilities are usually a one-time expenditure and vary widely from program to

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[*]In this study, all costs are expressed in constant dollars. Discounting may change some of the findings, depending on the distribution of cost outlays over the time horizon of interest and the discount rate assumed.

Table 1

CLASSIFICATION OF LIFE-CYCLE COSTS

Cost Element	Acquisition	Ownership	Weapon-System-Related
RDT&E	X		
Flight test	X		
Tooling	X		
Proc. of install engine	X		
CIP		X	
Spare engine		X	
Spare parts (base/depot)		X	
Depot labor		X	
Base labor		X	
ECPs—mod/retro	X	X	
AGE (peculiar/common)	X	X	
Transportation	X	X	
Management	X	X	
Facilities	X	X	
Training	X	X	
Engine attrition			X
Fuel			X

program. They are included in the definition, but will not be considered further in this study. With the increasing complexity of new weapon systems, peculiar support equipment may become increasingly costly, particularly if it is considered to include software design and development as well as hardware, and if simulators and diagnostic systems are regarded as support equipment. This should be considered in future systems, particularly if engine health monitoring becomes an increasingly important factor in the design of new engines.

Engine attrition and fuel are classified as weapon-system-related because these cost elements depend primarily on the design and use of the particular weapon system. (Fuel consumption is a function not only of engine design but also of mission use; attrition rates depend on single-engine versus multi-engine application as well as other features.)

AIRCRAFT TURBINE ENGINE DATA

Researchers attempting a life-cycle study of a weapon system constantly run up against the same obstacle: obtaining all the relevant data required. The problem is much like trying to put together a jigsaw puzzle when some of the pieces are missing and other pieces seem to have wandered in from another similar puzzle. Not only must the

researcher comb through a large number of data systems, but there is
the additional problem of inconsistency of data sources--two different
data systems not agreeing when both supposedly use the same data from
the same basic source.

The data most readily available for ownership cost-estimating in
this study have been aggregated, heterogeneous, and cross-sectional,
that is, gross weapon-system level or engine-family cost totals for
only a few fiscal years and sometimes inconsistently defined across
those years. A sound life-cycle analysis requires disaggregated, homo-
geneous, longitudinal cost data broken down below weapon-system level
into consistently defined categories and available over a considerable
period of time, preferably at least ten years. In general, military
practice is to save costs for about three to four years.

For engines, the contractor is the best source of RDT&E/CIP and
procurement data, since he is in the best position to break out the
detailed cost elements for each portion of the costs associated with a
particular contract, and he saves cost data for many years. These data
are valuable to him for analyzing new engine programs, whereas the
military services, because specific contracts may cover a multitude of
items procured by a lump-sum cost, are hard pressed to attempt a detailed
breakout of costs long after the fact. For instance, an Air Force con-
tract may include not only the procurement of whole engines, but some
allotment to spare parts, management data, field support, and so forth.

The only source of all relevant ownership data is the using mili-
tary service. It is critically important to obtain all relevant costs
in a particular area. For instance, depot costs are a large expense
for engines. The total depot cost includes not only overhaul of whole
engines, but also repair of reparable parts for whole-engine overhaul,
the cost of expendable parts, modifications, and the repair of compo-
nents received directly from the field and returned to the field. Some
of these costs have not been included in previous studies attempting
to obtain total depot costs.

The operating base has similar data problems. This is one area in
which specific weapon-system costs are significantly lacking. To obtain
cost elements at the base, for example, the Resource Management System

(RMS) is useful for costs associated with specific base cost centers. This system provides the cost associated with operating the engine shop. However, several difficulties hamper the collection of engine-related base costs: The engine shop is not the only source of labor related to engines; costs associated with the engine shop involve fixing all of the engines on a base, not merely the engine type of interest; and costs are not separated by weapon system. The analyst therefore must exercise care in obtaining the correct costs properly allocated, or apply some estimation technique that includes allocation.

III. AIRCRAFT TURBINE ENGINE LIFE-CYCLE ANALYSIS METHODOLOGY

Aircraft turbine engines have been one of the most successful inventions of the twentieth century. In revolutionizing certain aspects of military warfare and commercial travel, they have provided to military and commercial users very large benefits for the costs they have incurred. The benefits include higher performance, which is the primary objective for the military, and higher reliability, lower cost, and improved efficiency and productivity, which are usually the commercial objectives. Costs have included large and continuing expenditures in early research, exploratory development, advanced development, independent research and development, and the funding of development, procurement, product improvement, and maintenance for specific engine programs.

Military mission requirements have expanded so that fighter aircraft now fly faster and farther and at higher altitudes or very close to the ground; transports can lift more payload, fly over a longer distance, and take off and land in shorter distances. Commercial aircraft are much more productive today in terms of ton-miles delivered with the advent of wide-bodied jets powered by high-bypass turbofans compared to piston engine aircraft or even first-generation turbojets.

The attainment of military or commercial performance, reliability, and efficiency levels requires the judicious use of available technology in determining not only the level of performance or reliability that can be attained, but when and at what cost. Performance, schedule, and cost must be considered in a total context at the system level. Performance and reliability are tied together by the schedule. There is a trade-off between increased performance or improved reliability with regard to the available technology at a specific point in time. If improved levels of both performance and reliability are desired, then additional technology is necessary and more time is required to achieve that level of technology maturation. This is evident from comparing the military and commercial experience, although currently commercial objectives are approaching those of the military in some aspects of performance as well as in attempts to maintain high reliability.

In looking at the history of the development of specific engine subsystems and aircraft systems, it can be seen that evolutionary improvements have been obtained during the past four decades. It appears that the benefits of new engine subsystems in specific applications, such as military fighter aircraft or commercial transports, have indeed been worth the technology R&D support. Thus, the overall evolutionary trend of aircraft turbine engine technology is providing substantial benefits for the costs that have been incurred, and this is true in both military and commercial applications.

There are two levels at which benefits and costs for engines are usually analyzed: (1) the macro-subsystem level (the overall engine's performance and installation in the aircraft system), and (2) the micro-component level (the part or component's impact on the engine and on the aircraft). At the macro-subsystem level, *parametric analysis* is usually employed to select the appropriate design point for a new system prior to extensive engineering design. The available data base of historical engine programs is utilized to obtain parametric relationships. At the micro-component level, detailed *engineering analysis* is usually employed in evaluating whether an anticipated improvement in cycle performance, or materials, or a new design technique for a particular part or component may be expected to provide a positive benefit. In both approaches value judgment plays a large role.

This section will present the methodology for a parametric life-cycle analysis of aircraft turbine engines. An example of a performance/schedule/cost parametric analysis at the engine subsystem/aircraft system level for the F100 engine and F-15 aircraft will be provided.

PERFORMANCE/SCHEDULE/COST CONSIDERATIONS[*]

The approach employed in this analysis is to use a proxy for the state-of-the-art advance in engines. The proxy is a time trend of a particular set of aircraft turbine engine characteristics at the U.S. military 150-hour Model Qualification Test (MQT) date. A multiple regression technique was used to obtain the equation that predicts the

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[*] For a more detailed description of the methodology, see Ref. 3.

trend of the 150-hour MQT; the significant variables were thrust, weight, turbine inlet temperature, specific fuel consumption, and a pressure term that is the product of the pressure ratio and the maximum dynamic pressure of the engine's operating envelope--all important performance and technology measures. The initial efforts in obtaining a trend for military engines concentrated primarily on performance measures since they were most readily available and the military process has been essentially performance-oriented. Many additional variables were examined but did not add significantly to the quality of the model obtained.

The data base for this approach consisted of 26 turbojet and turbofan engines spanning a 30-year time period of aircraft turbine engine history (1942 to 1972). Some of the technological highlights of this time period are shown in Table 2. Although sporadic surges of technological advance have occurred at various times in specific areas, the overall trend has been one of reasonably steady evolution. Time can therefore be used as a proxy for evolutionary change when evaluating performance/schedule/cost trade-offs in the selection of a new engine for a new aircraft.

The 26 engines in the data base are shown by date of start of development in Table 3; the detailed data appear in Table 4. The model and the data points are portrayed in Fig. 2. The 26 points are plotted by the number of quarters of years from an arbitrary origin, October 1942, when the first U.S. turbojet-powered aircraft flew. The equation obtained is displayed in the figure.

The statistical qualities of the model are very good, as is shown by the R^2 and standard error; the F and t tests for the model and coefficients were also extremely significant. Perhaps most important, all the variables have entered into the relationship in a manner consistent with theoretical considerations and operational experience.

As will be shown in the cost analysis to follow, the continuing development of engines after the completion of the MQT when they have entered operational military service is often more costly than the entire development program up to the MQT. As an illustration of the application of the time trend technique, an analysis was made of the

Table 2

SYNOPSIS OF AIRCRAFT TURBINE ENGINE DEVELOPMENTS

	Early 1940s (WW II)	Late 1940s	Early 1950s (Korean War)	Late 1950s	Early 1960s	Late 1960s (Vietnam)	Early 1970s
Engine Types							
	Turbojet	Turbojet	Turbojet, turboprop/turboshaft	Turbojet, turboprop/turboshaft	Turbojet, turboprop/turboshaft, turbofan	Turbojet, turboprop/turboshaft, turbofan	Turbojet, turboprop/turboshaft, turbofan
Trends in Engineering Development							
	Increased thrust	Augmentation	High pressure ratio, variable stators	Cooled turbine	Supersonic turbofan	High-bypass turbofan (military and commercial)	High thrust/weight
	Centrifugal to axial compressor	Two-position nozzle	Titanium begins to replace aluminum	Mach 3	Multidesign point mission	High-temperature turbine	High component performance
	Single-design point mission	Stainless steel, aluminum, conventional steel	Sustained supersonic flight	Small lightweight engines	Superalloy materials	Cooling techniques	High-temperature materials
	Limited use of high-temperature steels; primarily conventional steels	Higher pressure ratio, dual rotor	Small helicopter engines	Commercial turbojet	Lightweight design	3-spool rotor	Cooling techniques
			Reliability/durability	Subsonic turbofan	Component improvements	Compatibility/integration	Composite materials
			Moderately higher turbine temperature	Titanium and superalloy material improvements	Commercial turbofan	Increasing sophistication of development	
				Transonic compressor		Commercial technology and requirements becoming as advanced as military	
Companies							
	General Electric	Allison	Allison	Allison	Allison	Allison	Allison
	Westinghouse	Boeing	Boeing	Boeing	Boeing	Continental	Continental
		Curtiss Wright	Continental	Continental	Continental	Garrett	Garrett
		Fairchild	Curtiss Wright	Curtiss Wright	Curtiss Wright	General Electric	General Electric
		General Electric	Fairchild	Fairchild	Garrett	Lycoming	Lycoming
		Pratt & Whitney	General Electric	General Electric	General Electric	Pratt & Whitney	Pratt & Whitney
		Westinghouse	Lycoming	Lycoming	Lycoming		
			Pratt & Whitney	Pratt & Whitney	Pratt & Whitney		
			Westinghouse				

Table 3

DATES OF DEVELOPMENT INITIATION FOR THE U.S. AIRCRAFT
TURBINE ENGINE DATA BASE

Early 1940s	Late 1940s	Early 1950s	Late 1950s	Early 1960s	Late 1960s
J30 W	J40 W	J52 PW	J58 PW		TF34 GE
J31 GE	J42 PW	J65 CW	J60 PW		TF39 GE
J33 GE/A	J46 W	J69 C	J85 GE		TF41 A
J34 W	J47 GE	J75 PW	TF30 PW		
J35 GE/A	J48 PW	J79 GE	TF33 PW		
	J57 PW				
	J71 A				
	J73 GE				

NOTE: W = Westinghouse; GE = General Electric; A = Allison; PW =
Pratt & Whitney; C = Continental; CW = Curtiss Wright.

Table 4

TECHNICAL DATA FOR U.S. MILITARY AIRCRAFT TURBINE ENGINES

Engine	Turbine Inlet Temp. (°R)	Thrust Max. (lb)	Weight (lb)	Pressure Term (lb/ft²)	Specific Fuel Consumption (lb/hr/lb)	Mach No.	Max. Dia. (in.)	Length (in.)	MQT (qtr)
J30	1830	1560	686	1575	1.17	0.9	19.0	94	17
J31	1930	1600	850	1710	1.25	0.9	41.5	72	11
J33	1960	3825	1875	3400	1.22	1.0	50.5	103	19
J34	1895	3250	1200	3400	1.06	1.0	27.0	120	27
J35	2010	4000	2300	3400	1.08	1.0	40.0	168	21
J40	1985	10900	3580	5750	1.08	1.8	41.0	287	45
J42	1825	5000	1729	3640	1.25	1.0	49.5	103	25
J46	1985	6100	1863	6625	1.01	1.8	29.0	192	44
J47	2060	4850	2475	5375	1.10	1.0	37.0	144	26
J48	2030	6250	2040	4880	1.14	1.0	50.0	107	33
J52	2060	8500	2050	12840	0.82	1.8	31.5	150	74
J57	2060	10000	4160	11400	0.80	1.4	41.0	158	41
J58	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	87
J60	2060	3000	460	10360	0.96	1.0	24.0	80	71
J65	2030	7220	2815	8500	0.92	1.8	38.0	127	46
J69	1985	920	333	3400	1.12	1.0	22.0	44	56
J71	2160	9570	4090	11000	0.88	1.5	40.0	195	47
J73	2060	8920	3825	8750	0.92	1.9	37.0	147	49
J75	2060	23500	5950	16724	0.80	2.0	43.0	259	59
J79	2160	15000	3225	18056	0.87	2.0	37.5	208	57
J85	2100	3850	570	10360	1.03	2.0	20.0	109	74
TF30	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	92
TF33	2060	17000	3900	19240	0.52	1.0	53.0	136	71
TF34	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	120
TF39	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	109
TF41	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	107

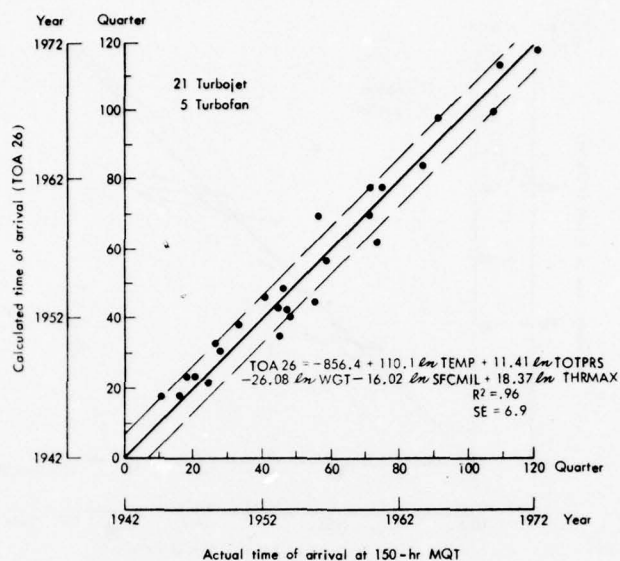[a]Deleted for security or proprietary reasons.

Fig. 2--Military turbine engine time of arrival

additional technological growth of 13 engines after their original MQT. It would be expected intuitively that the growth version of an engine already in production would have limited design flexibility, because many of its features are constrained by the existing hardware and production capabilities. Hence, technology improvement for updated engines should be slower than that for new engines. This expectation is borne out by Fig. 3, portraying post-MQT technology growth for 13 engines. The left-hand point of each pair of points is the original MQT engine, and the right-hand point is the most improved version. The connecting line indicates the rate of technological growth for each engine relative to the state of the art. All engines showed growth curves of less than 45 degrees.

To compare commercial experience with the military, a commercial engine data base of 11 points was also obtained. The detailed data for these engines are in Table 5. The results for the 11 data points relative to the time trend are shown in Fig. 4. The commercial trend line lies below and appears to be approaching the 45-degree-line military model as time increases. The implication is that commercial engines are more "conservative" than their performance-oriented military
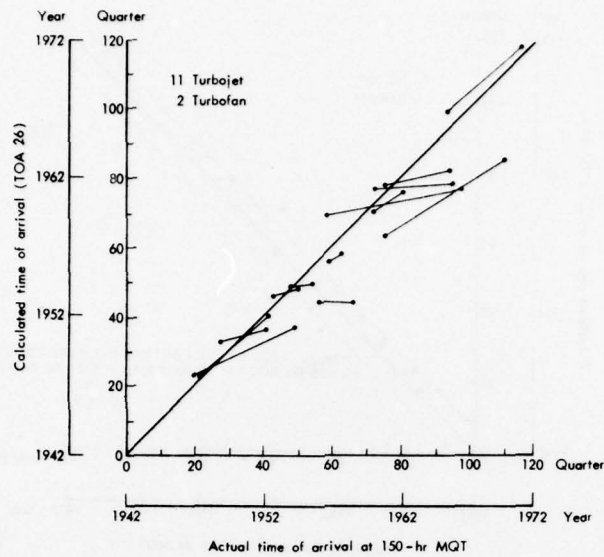
Fig. 3--Military growth engine time of arrival

Table 5

TECHNOLOGY DATA FOR COMMERCIAL U.S. TURBINE ENGINES

Engine	Turbine Inlet Temp. (°R)	Thrust Max. (lb)	Weight (lb)	Pressure Term (lb/ft^2)	SFC (lb/hr/lb)	MQT (qtr)	Period of Development Initiation
JT3C	1995	13,500	4234	11,050	0.78	59	Late 1950s
JT4A	1995	15,800	5020	10,200	0.80	59	Late 1950s
JT3D	1995	17,000	4150	11,050	0.52	71	Late 1950s
JT8D	2180	14,000	3160	13,600	0.59	81	Late 1950s
JT12	2000	2,700	465	5,525	0.96	71	Late 1950s
CJ805-3	2100	11,200	2800	11,050	0.83	71	Late 1950s
CJ805-23	2100	16,100	3800	11,050	0.56	77	Late 1950s
CJ610	2060	2,850	399	5,780	0.99	82	Early 1960s
CF700	2100	4,125	725	5,525	0.65	87	Early 1960s
JT9D	(a)	(a)	(a)	(a)	(a)	107	Late 1960s
CF6	(a)	(a)	(a)	(a)	(a)	112	Late 1960s

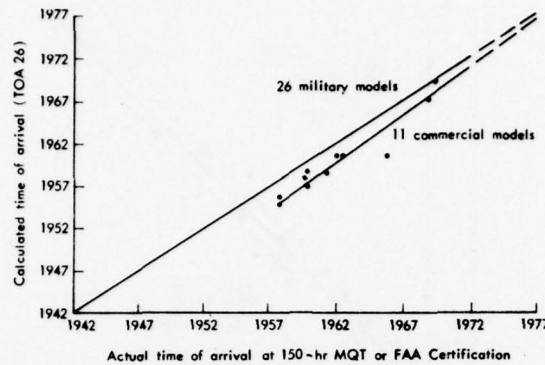^{a}Deleted for security or proprietary considerations.

Fig. 4--Comparison of military and commercial aircraft
turbine engine time of arrival

counterparts. It also appears that the commercial line is converging
with the military model, indicating that commercial engines may approach
military engines in the future. Indeed, some engine designers feel that
commercial technology could surpass military technology in the future,
especially if noise abatement and smoke elimination requirements are
explicitly considered. All commercial engines were direct derivatives
of military programs until development of the Pratt & Whitney JT9D.
The JT9D is the first example of a major new U.S. aircraft turbine en-
gine entering commercial service with no prior military experience.
Another possible factor is the absence of new military programs in the
early 1960s.

The 11 commercial engines were then added to the data base of 26
military engines, and an equation was obtained that uses the combined
37-point data base. A dummy variable (MCDUM) was employed for the
commercial engines to differentiate them from the military. The results
are shown in Fig. 5. The indication is that the commercial engines are
more conservative than military engines because of their higher reli-
ability goals. The dummy variable has a positive value of about ten
quarters, indicating that commercial engines are about 2-1/2 years
behind military engines.

The relationship obtained for the performance characteristics
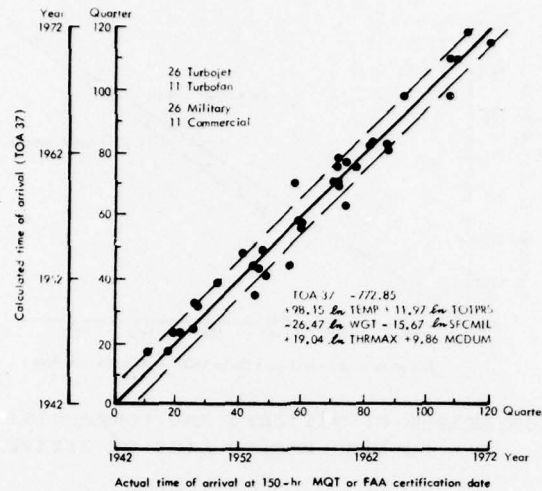sought by the military or commercial user over time can serve as a

Fig. 5--Military and commercial turbine engine
time of arrival

proxy for the measurement of the state of the art with time. In this
analysis, not only the time trend but also a time difference (the
characteristics sought at a certain date compared with when those
characteristics were expected to arrive) are employed in a series of
cost models to obtain a life-cycle cost for engines. These models are
useful to ascertain the cost effect of not only the trend of the state
of the art, but also whether a particular engine is "pushing" the state
of the art relative to the trend of time and how that might affect cost.

Table 6 presents the models obtained to date.[*] The state-of-the-
art trend (time of arrival) is shown with the other important charac-
teristics sought in an engine, as discussed above. In addition to all
of the models having statistical significance, the variables entering
the models are perceived to behave correctly with regard to theoretical
relationships; they corroborate the experience of the designers and
users that the direction of the variables is correct, giving additional
confidence to the validity of the models. This is true for all the
models presented. For instance, in the state-of-the-art trend, where

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[*]Additional details are shown in Ref. 3.

Table 6

MILITARY LIFE-CYCLE ANALYSIS
(In 1975 dollars)

State-of-Art Trend $R^2 = .96$ SE = 6.9 F = 92.0 (5, 20)	TOA26 = 856.38 + 110.10lnTEMP + 11.11lnTOTPRS − 26.08lnWGT − 16.02lnSFCMIL (5.8)[a] (3.1) (5.1) (2.8) + 18.37lnTHRMAX (2.8)
Development Cost ($M) $R^2 = .96$ SE = .18 F = 55.7 (4, 9)	lnDMQTC = 1.3098 + 0.08538DEVTIME + 0.49630lnTHRMAX + 0.04099△TOA26 + 0.41368lnMACH (7.6) (7.1) (4.9) (2.3)
Component Improvement Cost ($M) $R^2 = .88$ SE = .29 F = 60.5 (3, 22)	lnCIP = 2.79026 + 0.78862lnTHRMAX + 0.04312 TOA26 + 0.00722OPSPAN (9.1) (5.7) (2.5)
Total Development Cost ($M) $R^2 = .94$ SE = .18 F = 111.8 (4,29)	lnTDC = 0.97355 + 1.23809lnMACH + 0.07345lnQTY + 0.10386lnTHRMAX + 0.00918 TOA26 (10.3) (6.8) (8.5) (2.1)
1000th Unit Cost ($M) $R^2 = .95$ SE = .215 F = 63.0 (4,13)	lnKPUSP = −8.2070 + 0.70532lnTHRMAX + 0.00674TOA26 + 0.45710lnMACH + 0.01804△TOA26 (9.2) (2.8) (2.6) (2.4)
Cumulative Production Quantity Cost ($M) $R^2 = .97$ SE = .22 F = 501.7 (6, 81)	lnPRQTYC = −7.8504 + 0.8697lnQTY + 0.82204lnTHRMAX + MFRDUM + 0.01858△TOA26 (45.) (24.) (6.) (5.) + .34478lnMACH + 0.00277TOA26 (4.) (2.4)
Depot Maintenance Cost Per Engine Flying Hour Restored ($/EFHR) $R^2 = .97$ SE = .22 F = 67.6 (4, 7)	lnDCEFHR = 2.76182 − 0.90604lnATBO + 1.26074lnCPUSP + 0.01104OPSPAN − 0.02245 TOA26 (10.2) (4.2) (2.2) (1.9)
Base Maintenance Cost Per Engine Flying Hour Consumed ($/EFHC) $R^2 = .79$ SE = .26 F = 10.0 (3,8)	lnBMCEFHC = 3.50819 − 0.47457lnMTBO + 0.01299OPSPAN + 0.56739lnCPUSP (4.5) (2.2) (1.6)

NOTE: See List of Symbols for definitions of terms.

[a] t statistics.

it is expected that technology will be improving with time, turbine inlet temperature is a highly desirable characteristic in an engine; it has indeed improved with time, and we do have a positive coefficient for how it enters the time trend relationship. Variables that would be expected to be reduced with time, such as weight and specific fuel consumption, have negative coefficients. Thrust is positive; the average thrust size of engines has been growing with time.

We use time trend parameters (TOA and ΔTOA) in the cost models. For instance, a model for development cost has been obtained. Here, the development cost of the engine to the 150-hour MQT is a function

of the development time period (how long the engine was under development), thrust (the physical size of the engine), the Δ time trend (how the engine compared to the time trend), and the complexity of the engine (Mach number measuring the flight environment). All of these variables enter positively, all having the effect of increasing the development cost of the engine. We see similar results in looking at production costs. We show several ways of achieving development and production costs. Thus, a method for trading off the acquisition performance/schedule/cost for a new engine is presented.

To complete an analysis of engine life-cycle cost, models for depot and base costs are required. These two areas are principal cost elements in ownership of engines (in addition, whole spare engines and CIP are also considered part of ownership in this study). Note that these two models each use a different definition of engine flying hour, the utilization measure that was used for engine ownership costs. Costs incurred at the air base depend on "consumed" flying hours, the flying hours "restored" by the depot; that is, the depot repairs engines and restores flying time to the engines and returns them to the user. In a steady-state situation of supply equal to demand, the user is demanding (consuming) in the field and the depot is supplying (restoring) to flying status. Thus, in a steady-state situation, consumed and restored flying hours would be approximately the same. A problem arises in the analysis because the life cycle is dynamic. Furthermore, we have only limited cross-sectional data at the depot (for a year or two) and in any given year the consumed and restored flying hours can be very different. For instance, in the initial phase of a program when new engines are being introduced, the fleet may be flying at a high rate, yet not many engines would be showing up at the depot until time is accumulated on them. Thus, consumed flying hours are much higher than restored hours. Also, across the total program, consumed hours would exceed restored hours because when an engine is finally condemned and disposed of, it has some flying hours on it (it is not sent back to the depot to be restored to zero time before being thrown away). Thus, more hours are consumed than restored during the engine life cycle. In any particular year, however, more engine hours may be restored in the depot

than consumed in the field (for example, a major modification program may cause engines to be sent to the depot for repairs even though they have accumulated relatively few hours). Thus, these two measures are important to understand and keep separate; in the depot, the restored flying hour is the preferred unit for tracking depot costs, and at the base, the consumed flying hour is the preferred unit for tracking base costs.

The key independent variables for depot and base costs are time between overhaul and current unit selling price of the engine. At the depot, the average time between overhaul (ATBO) is of interest--when an engine actually comes in to be fixed. At a base, the maximum time between overhaul (MTBO) is of concern since it is the policy that sets how long an engine can stay in the field before it is mandatory for it to be returned to the depot for overhaul. This is of interest at the base because the base keys its scheduled periodic inspection, which is a major part of the propulsion shop workload, to the MTBO. It is also interesting to note that the engine unit selling price indirectly brings into the cost relationships the state of the art in terms of TOA and ΔTOA because they were utilized in determining the production unit price. Thus, the time of arrival technique is indirectly represented in the depot and base cost estimation models.

IV.   PARAMETRIC ANALYSIS AT THE ENGINE SUBSYSTEM/AIRCRAFT SYSTEM LEVEL

How have the costs of fighter engines changed over the past decades? Does technology improvement have a payoff? The F-15 will be presented as an example of subsystem/system level analysis intended to provide some insight into the value of engine technology improvements. But first the performance/cost trends of fighter engines will be discussed.

ENGINE SUBSYSTEM LEVEL ANALYSIS

Figure 6 presents a hypothetical baseline program to calculate on a common basis life-cycle costs for various fighter aircraft engines employed in the 1950s, 1960s, and 1970s. Costs are in constant 1975 dollars; no discounting has been employed in this example, nor are any costs allocated for fuel or attrition due to a specific application. The engines were all "advanced" for their time.

Using the models derived, Fig. 7 presents a comparison of life-cycle cost breakdowns for these hypothetical engine programs. In spite of increases in development and procurement costs of engines (in constant dollars) from one decade to the next, the ownership cost portion dominates and tends to represent an increasingly larger portion of the total. Depot maintenance cost, the largest cost, is the reason for this trend. Miscellaneous costs were estimated to be approximately 3 percent of total costs for this example. The table indicates that total life-cycle cost has more than doubled from the 1950s to the 1970s and that the depot is accounting for an increasing portion of that larger cost. It must be remembered that the 1970s engine is significantly more advanced in technology, and is larger in thrust and faster in Mach number, than the 1950s engine, and those improvements are what the military is paying for in attempting to obtain better weapon systems.

When these engines are normalized to the trend of technology advance and the same thrust and Mach number as the 1950s engine, the second set of bars is obtained (Fig. 8). Analysis reveals that present

A LIFE-CYCLE COST EXAMPLE
FIGHTER ENGINES 1950s/1960s/1970s
(J79) (TF30) (F100)

HYPOTHETICAL PROGRAM: 1975 DOLLARS

                                   5 YEAR DEVELOPMENT (ADVANCED ENGINES)

                                   15 YEAR OPERATIONAL SPAN

                                   6 MILLION ENGINE FLYING HOURS CONSUMED (OPERATIONAL)

                                   5 MILLION ENGINE FLYING HOURS RESTORED (DEPOT REPAIR)

                                   1935 ENGINES

                                   90% LEARNING (PRODUCTION)

                                   750/1200 ATBO/MTBO

NO FUEL OR ATTRITION INCLUDED

Fig. 6

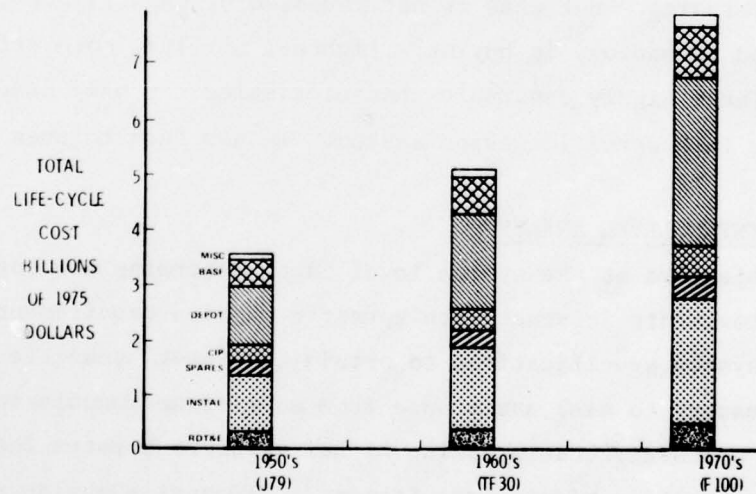# LIFE-CYCLE COST TREND EXAMPLE
ADVANCED ENGINES: GROWTH THRUST, MACH

Fig. 7

LIFE-CYCLE COST TREND EXAMPLE
ADVANCED ENGINES: GROWTH THRUST, MACH
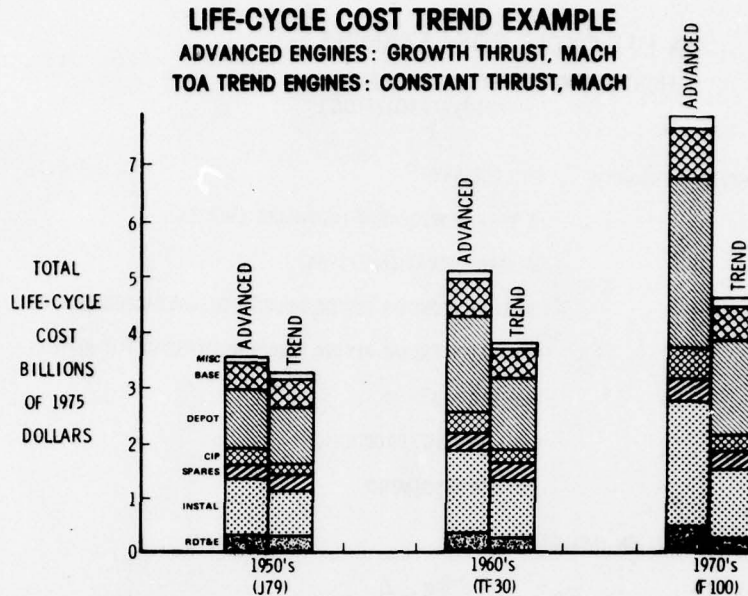TOA TREND ENGINES: CONSTANT THRUST, MACH

Fig. 8

engines with higher technological content are more expensive than their older counterparts. But what is not revealed by this figure is what the improved technology is buying: lighter, smaller, more efficient engines. These highly desirable characteristics can only demonstrate their value in a specific weapon system. We now turn to such an example.

AIRCRAFT SYSTEM LEVEL ANALYSIS

The objective at the system level is to determine how engine technology improvements interact with specific mission requirements and system/subsystem specifications to obtain the "best" possible design. It was necessary to seek assistance from an airframe manufacturer to obtain the necessary understanding of how system/subsystem interactions depend on a specific mission requirement. McDonnell-Douglas provided assistance in examining an air superiority mission requirement. The Rand engine life-cycle models and Rand airframe RDT&E and procurement models were then utilized, together with the airframe information on system design and fuel consumption for the particular mission requirement, to determine the costs that are given here.

Certainly, "optimum" answers were not obtainable for the time and effort involved in this illustrative analysis, but this example can give system-level trade-off considerations, which in turn improve the perception of the usefulness of the subsystem results.

The F-15 air superiority mission was investigated at the system/subsystem level. This illustrative analysis is of limited scope. A total optimization study for each particular mission requirement, variation of engine thrust/weight, engine thermodynamic cycle, and aircraft configuration would have resulted in a very complex analysis.[*] For this example, a range of engine thrust/weight ratios was studied for a family of state-of-the-art engines of the 1960s, 1970s, and 1980s. For analytical simplicity, the thermodynamic cycle of the F100 engine was used throughout the analysis and a fixed procurement of twin-engine aircraft at a constant airframe technology was an additional ground rule.

Figure 9 presents the results of the variation of parametric aircraft takeoff gross weight designs with changes in engine thrust/weight ratio for the McDonnell-Douglas F-15 air superiority mission payload and performance. The improvement obtained in reducing aircraft takeoff gross weight as thrust/weight ratio is doubled is particularly evident. The design point for the F-15 is shown. It is seen that a considerably smaller aircraft gross weight (and engine thrust size) results as engine thrust/weight increases. It should be noted that further improvements in thrust/weight ratio apparently provide much less reduction in airframe takeoff gross weight *for this particular air superiority mission*. Aircraft trade-offs assume equal reliability and availability.

A hypothetical system baseline program is presented in Fig. 10. In this case, the fuel costs and airframe development and procurement costs are also discussed. For this F-15 air superiority mission, the F100 engine was calculated to consume 1250 gallons of fuel per average flight

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[*] An extensive study investigating variations in all these areas would normally be accomplished during concept formulation for a new weapon system.

MISSION REQUIREMENT IMPACT ON AIRCRAFT TAKEOFF
GROSS WEIGHT AND ENGINE THRUST/WEIGHT TRADEOFF

- Fixed Force Size
- Twin Engine Configurations

RELATIVE AIRCRAFT TOGW

2.00
1.75
1.50
1.25
1.00
0.75

McDonnell F-15 Air Superiority Mission
(Fixed F 100 Engine Cycle—Fixed F-15
Airframe Technology)

.5   1.0   1.5
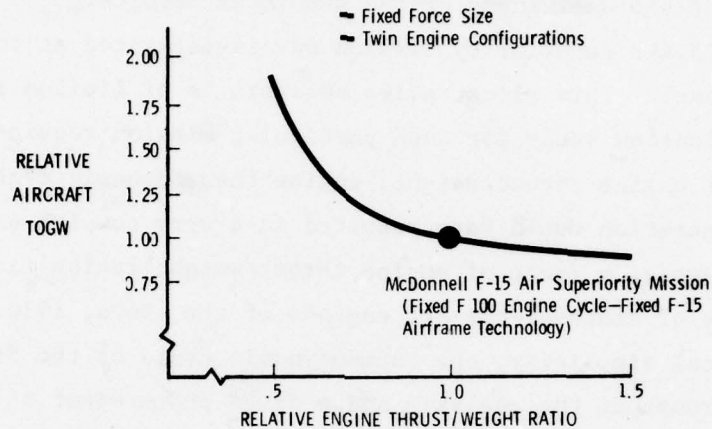
RELATIVE ENGINE THRUST/WEIGHT RATIO

Fig. 9

HYPOTHETICAL BASELINE PROGRAM

ENGINE

- 1975 DOLLARS
- 5 YEAR DEVELOPMENT
- 15 YEAR OPERATIONAL SPAN
- 6 MILLION ENGINE FLYING HOURS CONSUMED (OPERATIONAL)
- 5 MILLION ENGINE FLYING HOURS RESTORED (DEPOT REPAIR)
- 1935 ENGINES PROCURED
- 90% LEARNING (PRODUCTION)
- 750/1200 HRS ATBO/MTBO

FUEL

- F15/F100 – 1250 GAL/FH @ 44¢/GAL WITH FUEL
  CONSUMPTION SCALED TO THRUST
- ATF/F100 – 1100 GAL/FH @ 44¢/GAL WITH 10%
  SFC IMPROVEMENT FOR ADVANCED ENGINE

AIRFRAME

- 1975 DOLLARS
- 729 AIRFRAMES PROCURED
- RDT&E AND PROCUREMENT ONLY
- FIXED AIRFRAME TECHNOLOGY

Fig. 10

hour (at 44 cents per gallon) with fuel consumption at other engine thrust/weight design points scaled to the thrust of the engine. At a thrust/weight ratio of four, for example, the aircraft takeoff gross weight is double that of a thrust/weight ratio of eight. Fuel consumption was scaled to thrust level. The number of airframes procured is consistent with the number of engines being procured. RDT&E and procurement costs assume fixed airframe technology; no airframe operating and support costs were estimated. Again, in this case the airframe technology remained constant and only the thrust/weight ratio varied.

The cost results for the air superiority mission at selected engine thrust/weight values corresponding to aircraft gross weight are presented in Fig. 11. The thrust/weight ratio of eight is the design point for the F-15. The figure indicates that for the air superiority mission requirement, increasing the engine thrust/weight ratio lowers the total system costs, even though more technology is required, resulting in a more expensive engine. Total cost comprises the engine life-cycle cost, airframe RDT&E and procurement cost, and fuel cost. The cost is lower when using the more advanced engine because the physical size and weight of the engine and airframe are reduced, resulting in a smaller airframe to achieve the same mission. Improvement in thrust/weight from eight to twelve results in little additional cost reduction because the size of the airframe is not reduced as much and because the specific fuel consumption is the same (only the thrust/ weight ratio for the engine is varied). Figure 12 shows a second set of bar charts in which a 50 percent improvement in ATBO/MTBO for the engine is presented. Again, notable savings for the engine are achieved, particularly because of cost reduction at the depot. Thus, *in this particular air superiority mission*, it would appear that use of advanced technology, resulting in a 50 percent increase in ATBO/MTBO, would reduce costs more than if the same technology advance were used to increase the thrust/weight ratio from eight to twelve. Overall, advanced technology (from 1950s to 1970s) apparently saved several billion dollars in this one fighter application in terms of gross weight reduction of the aircraft system, and further savings are possible if aircraft turbine engine endurance as well as performance can be appreciably improved.

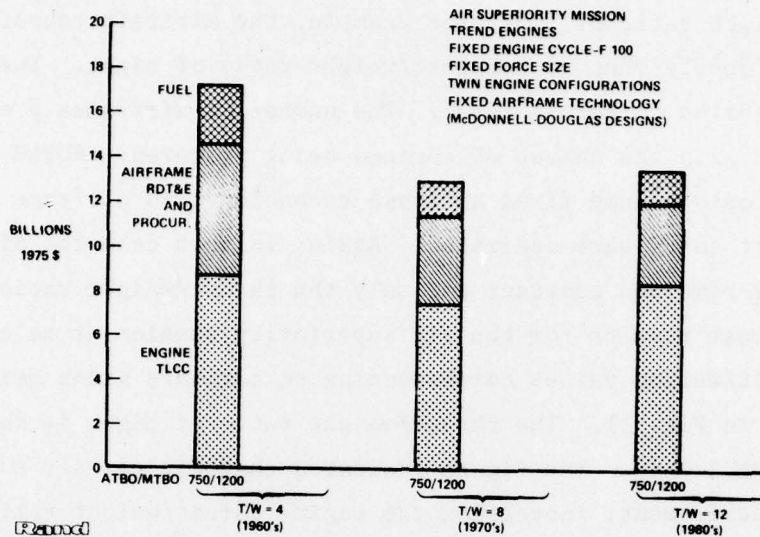## SYSTEM-LEVEL COST DIFFERENCES WITH ENGINE THRUST/WEIGHT VARIATIONS

Fig. 11

SYSTEM-LEVEL COST DIFFERENCES WITH ENGINE THRUST/WEIGHT AND DEPOT REPAIR VARIATIONS
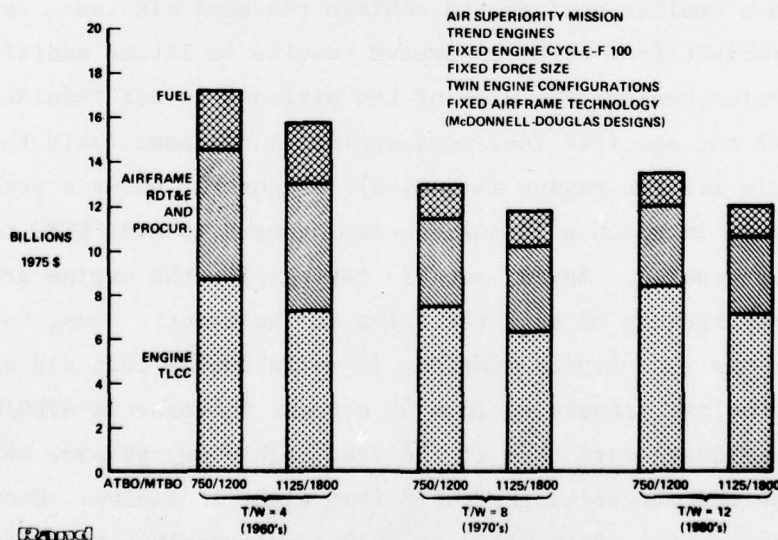

Fig. 12

V. COMMERCIAL CONSIDERATIONS

What lessons can be learned from commercial experience that might be relevant to the military? The primary concern of an airline is to make a profit, and the primary operational benefit measure for an airline is aircraft utilization. For engines, utilization is usually expressed in flying hours or operating cycles. The commercial flying-hour experience is considerably different from the military. The airlines follow established routes with known demand rates for flying-hour segments and takeoffs and landings over a given calendar period. The U.S. military has varying requirements, except perhaps for a portion of the fairly well-scheduled airlift fleet. The airlines accumulate engine operating hours faster than the military, even for comparable aircraft. The airlines fly about three times more hours in a given year than the airlift fleet aircraft, and ten times more than supersonic fighter aircraft. But are there commercial operational and maintenance practices that the military might consider to improve their capabilities?

OPERATIONAL PRACTICE

Commercial operational practices and procedures also differ from those of the military. Operationally, the airlines require pilots to devote considerable "tender loving care" to their aircraft. The throttle is used only to the extent made necessary by gross weight, field length, altitude, and temperature for takeoffs and landings. On almost all Air Force aircraft, there is no way to determine how much "hot-time" the engine accrues during a known mission profile, although there has been some initial work on engine diagnostic systems that count throttle excursions. (The F100 engine on the F-15 aircraft has such a counter, but it is not yet working well in operational practice.) Squeezing out the last percent of power is considered very costly to engine hot-section life. Airlines require flight crews to monitor engine performance in flight and to supply data for trend analysis of engine performance after each flight. Careful throttle management enables

the airlines to achieve important dollar savings by trading performance for temperature (and thus parts life). The Air Force could do the same. Since the military operation of an engine is even further up on the higher end of the power curve (approaching maximum performance), even a nominal reduction in throttle excursions could yield a significant improvement in parts life.

MAINTENANCE PRACTICE

Commercial maintenance practice has been extolled as an example the military might emulate. Airline maintenance practice today has turned away from the military's "hard-time" philosophy (certain actions are taken at certain times regardless of how well the engine is operating) toward what is generally termed on-condition maintenance.

There is some semantic confusion concerning the meaning of on-condition maintenance. Current airline maintenance procedures fall into three areas: maintenance of life-limited, high-time parts; condition monitoring of certain nonsafety-of-flight parts for which there are no fixed time limits; and on-condition maintenance of critical safety-of-flight parts that require regular periodic inspections. Various airlines cause confusion by using these terms somewhat differently, but in general they distinguish between on-condition maintenance and condition-monitored maintenance by the level of inspection activity and the effect of the part on safety of flight.

The intent of the on-condition maintenance program is to leave the hardware alone as long as it is working well and symptoms of potential problems are not developing. This philosophy is *not* one of "fly-to-failure" when safety-of-flight items are involved. This maintenance program is expected to reduce the shop visit rate, determine which parts are causing removals and at what time intervals, increase the engine's accumulation of flying hours and cycles by maintaining its availability on-wing, reduce secondary damage resulting from serious failures, and maintain and improve the normal distribution of failures expected for engines.

Prolonging the interval between shop visits for maturing commercial engines is equivalent to increasing the average time between overhauls

in the military. The result of this action is to prevent the truncation of the engine overhaul distribution caused by fixing the maximum allowable operating time between overhauls and the subsequent large increases in engine removal rate when maximum hard-time overhaul is reached. Commercial practice could therefore provide insights to the military on what parts are determining failure rates and how CIP funds might best be apportioned among various engine problems.

On-condition maintenance has several specific requirements: (1) periodic on-aircraft inspection of engine safety-of-flight areas at ground stations (borescoping, X-ray, oil sampling and analysis, careful examination of the engine); (2) engine performance checks and data gathering in flight, where the data are used for trend analysis at a central data-processing center (usually at the main overhaul facility) to anticipate problems before they occur; and (3) tracking of critical parts by part number to keep account of the amount of operating time and operating cycles the parts have undergone.

When an engine problem is discovered or anticipated from trend analysis, the engine is removed from the airframe and repaired at a base if possible (by replacing a part or module, which is then returned to the shop); or the entire engine is sent back to the shop; or the aircraft is scheduled for a flight to the maintenance base so that the engine can be removed and another engine installed overnight with no loss of scheduled flight time. It is estimated that 90 percent of engine repair activity is performed at the shop; very little fixing of hardware is done at bases except removal and replacement of engines or modules or of major parts easily reached with minimum disassembly. (The base also performs other tasks primarily concerned with ground inspections, and handles lube, oil, and maintenance associated with day-to-day activities.) It may be asked why the Air Force cannot operate in this manner. The reason is that the airlines operate in a relatively stable peacetime environment. Some Air Force units may be able to operate in a similar manner, but others must be prepared to be self-sufficient in an overseas wartime contingency and thus are required to maintain a larger labor force at the base level.

When a commercial engine is returned to the shop, the data system is expected to furnish the engineering and maintenance people with

records of how much operating time has accumulated on particular parts so they can judge whether to fix only the part that is broken (or that they anticipate will break shortly) or to fix other parts as well while they have the engine in the shop. They attempt to rebuild the engine to some minimum expected operating time.

Newer commercial engines are of modular design. Modular means that the engine can be readily separated into major subassemblies. The intent is to add flexibility to maintenance procedures at the shop and at the base. Engines can be removed and replaced overnight and modules can be "swapped out" at a base in several days, with only the modules returned to the shop for repair. One result is that airlines turn engines around faster than do U.S. military depots (15 to 30 days versus 45 to 90 days) and consequently require substantially fewer spare engines.

The U.S. Air Force has begun to procure modular-designed engines; the F100 engine on the F-15 is an example. The Air Force is implementing a modular engine maintenance information system like that of the airlines for keeping track of the operating time on parts and for helping in decisions concerning the operating life appropriate for each module and engine. The Air Force will have to be able to do this kind of analysis at the depot and base if it plans to adopt the commercial maintenance philosophy regarding modular engines and, especially, regarding on-condition maintenance.

Maintenance experience and skill levels are very high in airline central shops. Most mechanics are FAA-qualified, have a long continuity in service, and with their years of experience get to know the individual engines and aircraft, since the fleet is not so large for a given airline. The civilian labor force at the Air Force depot also has considerable continuity of service, but the base inventory and the current practice of completely disassembling an engine during overhaul and reassembling it with different parts prevents them from getting to know individual engines--besides which, the engine changes its identity every time through the depot. It is not clear how much of an edge this gives the airlines, but airline people consider it substantial. The commercial work force is also more flexible about scheduling overtime during peak periods and laying off during slumps. The military depot does not have this flexibility in the short term.

Several airline officials have expressed concern that they have gone too far too fast with on-condition maintenance as applied to current high-bypass-engine experience. Their worry is that they might be merely postponing certain problems to a later date. They believe they are obtaining more operating hours, but at a cost. When an engine finally does return to the shop, more has to be done to it in terms of parts replacement than if it had come in sooner. The problem is to determine the "optimum" point. The military attempt to do so by setting an engine MTBO at some point that the user and supplier believe is the optimum in terms of operational availability on the one hand, and the amount of work required when it is returned to the depot, on the other hand. The choice lies between the two extremes; a short-fixed-time philosophy is one, and on-condition maintenance running to failure or close to the anticipated point of failure is the other. There may be some optimum intermediate point derived from a combination of hard-time and on-condition maintenance, and this optimum could vary, depending upon the individual airline or military situation. One airline's (or service's) optimum is not necessarily another's because of differences in route structure and operating conditions (mission), utilization of the fleet, economic environment, and so forth. At any rate, it would appear desirable for the military to move away from its strict hard-time philosophy, but no doubt there is some point on the on-condition maintenance spectrum beyond which it may not be desirable to go for the sake of economic efficiency. Appropriate data are required to assist in seeking this optimum.

COMMERCIAL ENGINE COSTS

What does it cost the airlines to own and operate their commercial engines? Do they do a better job at cost control than their military counterparts? These questions are more difficult to answer than would first appear, even though manufacturers preserve a great deal of engine cost data over a period of time for their cost analyses. (Airlines are also required to provide certain cost data to the Civil Aeronautics Board (CAB), separated into certain cost categories.)

Because accounting practices, operations, and economics vary among airlines, however, only the individual airline will know fully what its costs are under its own accounting practices, route structure, operating environment, seasonal adjustments, and economic conditions. Therefore, difficulties arise in attempting to use airline cost data directly. The purchase price of an engine that an airline reports to CAB may reflect the cost of the entire pod, which is the total installed engine in its nacelle ready for mounting on the aircraft wing, or it may reflect the bare engine and certain spare parts. It may also include, as in the case of reported Air Force contract prices, spare parts and accessories, technical data, and field service costs. Thus, it may be difficult to use the aggregated data reported to CAB to arrive at standardized procurement costs that will be comparable among the commercial airlines. At least an estimate can be obtained, however, if it is known whether the purchase was for a bare engine or a podded engine, and if some idea can be gained of what additional costs are involved in the purchase price.

The matter of proprietary information can be a further stumbling block. To gather information on military engines for this study, it was necessary to go to the manufacturers for disaggregated, homogeneous, longitudinal data. They were willing to supply military data on a proprietary basis, but they were not willing to supply commercial cost data at all, except in the most unusual circumstances and then only on a very limited basis.

In sum, the analyst faces the dual difficulty of determining the content of the CAB data and of obtaining information the airlines and manufacturers consider highly proprietary. Thus, the major problem in comparing commercial and military engines is generating comparable costs. At present, the most pressing need is to understand what the commercial cost data actually include; nor is it sufficient to do so for only a one-year or two-year cross-section. Cost analysts in both the engine industry and the airline industry agree that five to seven years worth of historical data are needed to gain a reliable picture of the trend for a particular piece of equipment. This appears to be true for both technical and economic reasons.

Analysis of Available Data

Figure 13 depicts an approximation of typical 14-year life-cycle costs for the older first- and second-generation commercial turbojet and turbofan engines. New third-generation high-bypass engines may be different in terms of cost magnitude and proportions, and their life-cycle may be extended to cover their higher costs, with depreciation spread over more years--perhaps 16 rather than 14. The figure reveals that 75 to 80 percent of cost is ownership. It should be recalled, however, that the procurement cost of the engine includes allocations for development and IR&D, and certain ownership costs (spare parts purchases) also includes, besides CIP and warranty add-ons, a charge for development; consequently, acquisition and ownership costs are not cleanly defined even for airlines. It is interesting to note from the figure that an airline buys an engine twice over in spare parts alone during its operational lifetime.

Data obtained from five commercial airlines in the course of this study indicate that the older and smaller turbofan engines such as the JT8D and the JT3D are costing between $50,000 and $100,000 per shop visit for engines that have been operating for 2000 to 4000 hours, while the newer and larger high-bypass engines such as the CF6, JT9D, and RB-211 are costing between $100,000 and $200,000 (1975 dollars) per shop visit for engines that have been operating for 1000 to 2000 hours. The cost range appears to be affected by the size of the engine, the state of the art, engine maturity, usage since the last shop visit, and airline policy on refurbishment to some minimum operational time prior to the engine's next shop visit. The costs are quite different from those obtained from the military for comparable engines with similar operating experience. Airline shop costs are apparently fully burdened[*] and reflect around 90 percent of base and shop costs combined. At the military depot, a cost increment of at least 50 to 100 percent must be added to the major overhaul cost to obtain the total depot cost per engine processed in a given year.

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[*]Including all allocated materials, back shop labor, and overhead, except for major modifications, which are treated as investment rather than operating expense for tax purposes.
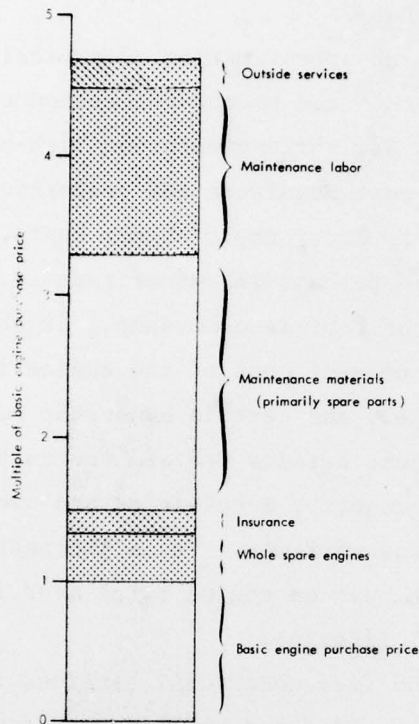
Fig. 13—Typical 14-year life-cycle costs for first- and
second-generation commercial turbojet and
turbofan engines

What does it cost to maintain a commercial engine? From the data
presented, ownership constitutes 75 to 80 percent of total life-cycle
cost (not including fuel). The first- and second-generation commercial
engines are estimated to have a peak cost of around $40 to $80 per
flying hour for ownership and $50 to $100 per flying hour total (all
costs are expressed in 1975 dollars). Steady-state costs with the ad-
vent of maturity fall to a range of $20 to $30 per flying hour for en-
gine maintenance. Peak costs appear to be two to three times steady-
state costs. A total of about 35,000 to 45,000 operating hours in a
14- to 16-year period is expected. New third-generation high-bypass
engines will peak at well over $100 per flying hour if the same per-
centage breakdown applies. The airlines hope that long-term steady-
state ownership costs can be reduced to around $40 to $50 per flying
hour when maturity is attained for these new-generation engines. Since

these engines are of higher technology, with at least twice the thrust
and considerably improved specific fuel consumption, they are expected
to be well worth the higher cost to the airlines in the service they
will provide with the new wide-bodied transports.

In examining the available commercial cost data over a number of
years, a general cost profile trend is distinguishable. A hypothetical
cost profile is shown in Fig. 14. It presents expected cost patterns
on the basis of consumed and restored engine hours with peak, average,
and steady-state values indicated. Also shown are two general problem
areas that seem to occur in engine maturation: an early peak (occur-
ring usually because of problems in the hot section in the engine's
maturation) and later on, an additional hump on the way to steady-state
conditions (some cold-section problems tend to show up later). Shop
visit rates show the same pattern (leading the reported cost data by
six to nine months because of reporting delays). The JT9D, operating
since 1970, apparently is approaching maturity and will be an inter-
esting example to watch as an indicator of cost differences between
the current generation of high-bypass engines and previous generations'
experience. It does appear that the high-bypass engines are at least
twice as costly to operate. The question still to be answered by the
operators is whether or not they will be as profitable as expected in
the long term. They were expected to return their investment and in-
crease airline profits when they were purchased in the late 1960s.
The difficulty has been the slower than expected increase in air trans-
portation growth in the early 1970s. One indication that things may
be different for a high-bypass engine is that some airlines are now
using 16 years as the depreciation period for tax purposes rather than
14 years, because these newer engines are not accumulating flying time
as rapidly as the older engines at similar points in their life cycle.
Consequently, the extra time is needed to achieve the expected 35,000
to 45,000 operating hours on the hardware.

In short, it is possible to construct a cost profile for the life
cycle of an engine. The data examined here are consistent with the
general trend indicated regarding maturation and steady-state opera-
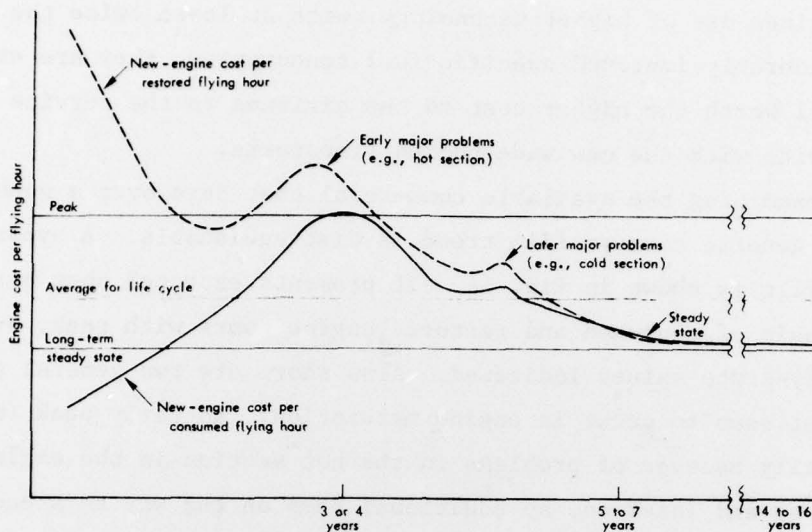tion. This commercial cost profile of peak, steady-state, and average

Fig. 14--Cost profile for commercial turbine engines

costs should be helpful in attempting to understand overall military
life-cycle costs, which should behave similarly (at perhaps a higher
cost level). The use of only cross-sectional data to estimate costs
for a given engine can be misleading if the engine's relative position
in its overall life cycle is not understood, and if the data are
heavily weighted to the steady-state situation, when overall average
costs are needed to determine overall life-cycle cost.

VI. ENGINE MONITORING SYSTEMS

How can operational data be obtained for users to understand day-to-day problems and costs, for military planners to obtain required data for engine life-cycle cost models, and for the engine designer to obtain the feedback necessary to improve current designs and future generations of engines? The use of engine monitoring systems has received increasing emphasis lately, with these objectives in mind. The experiences gained from several military and commercial aircraft turbine engine monitoring systems over the last decade and a half were examined in this light (see Ref. 4). Table 7 lists the six systems examined. They span the gamut of military and commercial, U.S. and British, and fighter and transport applications. The examination reveals that two different approaches to engine monitoring have evolved in attempts to achieve the varied goals of improved day-to-day engine operations, maintenance, and management, while reducing long-term support costs and providing feedback to engine designers. The first approach concentrated on the short-term day-to-day operations, maintenance, and management practices and was usually accomplished by recording in-flight data in a snapshot mode, i.e., a few seconds of data either at predefined performance windows or when certain engine operating limits are exceeded. The second approach focused on the long-term design-oriented cost reductions through improved knowledge of the engine operating environment. To achieve the design-oriented benefits, data must be recorded continuously on at least a few aircraft at each operational location for each type of mission.

U.S. monitoring systems have initially focused on short-term maintenance-oriented benefits, whereas the British initially developed a system that focused on long-term, design-oriented benefits. The benefits of each are listed in Fig. 15. From a life-cycle analysis viewpoint, it would seem that *both* types of benefits are worthy of consideration in any new monitoring system. Both countries are now moving in that direction.

Table 7

ENGINE MONITORING CASE STUDIES

System	Application (Engine/Aircraft)	Time Period
Time-Temperature Recorder	J57/F100D	1967-1969
Engine Health Monitoring System	J85/T-38A	1973-1977
Malfunction Detection Analysis Recording System	TF39/C-5A	1969-Present
In-Flight Engine Condition Monitoring System	TF41/A-7E	1973-Present
Airborne Integrated Data System	Commercial	1969-Present
Engine Usage Monitoring System	British Aircraft	Early 1970s-Present

SUMMARY OF ENGINE MONITORING SYSTEMS OUTCOMES

MAINTENANCE ORIENTED

● **OPERATIONAL**
- AWARE OF ENGINE HEALTH
- AWARE OF ENGINE OVERTEMPERATURES

● **MAINTENANCE**
- √ LESS MAINTENANCE MANPOWER
- √ LESS TROUBLESHOOTING & TRIM FUEL
- √ LESS ENGINE REMOVALS
- √ LESS PARTS CONSUMPTION
- ANTICIPATE MAINTENANCE (TRENDING)
- IMPROVE CAUSE & EFFECT UNDERSTANDING
- VALIDATE MAINTENANCE ACTION

● **MANAGEMENT**
- √ MODIFY TBO
- PROVIDE CONFIGURATION CONTROL

DESIGN ORIENTED
- GUIDE CIP
- CORRELATE TEST / DUTY CYCLES
- AID FUTURE ENGINE DESIGN

Fig. 15

In addition, ongoing engine duty-cycle research being conducted by the U.S. military services was also reviewed. This research demonstrates that neither the services nor the engine manufacturers have a clear idea of fighter aircraft engine operational usage--i.e., of power requirements and throttle transients on actual mission flight profiles. Figures 16 and 17 present one example for a U.S. Navy fighter, comparing the design power required cycle and actual mission power required cycles during operation. As a result of this lack of knowledge of the correct duty cycle, engine parts life has generally been overestimated and expected life-cycle costs have been understated. While this situation has improved during the past several years, further improvement is clearly needed. Expanded testing during an engine development program is one solution.

Much uncertainty exists about the benefits and costs (increases and reductions) attributable to engine monitoring systems. It is clear, however, that the narrow sense of cost savings over the short term should not be the sole criterion on which engine monitoring systems are judged. The potential benefits of anticipated maintenance, improving maintenance crews' understanding of problems as they arise, verifying that maintenance is properly performed, establishing relevant engine test cycles, and the effects of future engine design--all of which we are unable to quantify to date--have substantial value. This is especially so when the U.S. military services are moving to an on-condition maintenance posture as envisioned for the F100 and TF34 engines. Also, the modular design of the engines requires some type of sophisticated fault isolation as the engine matures if on-condition maintenance is to be applied at the engine component level.

The U.S. military continues to investigate and develop turbine engine monitoring systems for engines recently introduced into service and for future engines. The objectives of any new engine monitoring system should include the valuable contribution that continuous recorded data can make to the engine designer over the long term. Of particular importance to new engine design and new applications of current engines is the correlation between testing and operational duty cycles. Engines with different applications will have quite
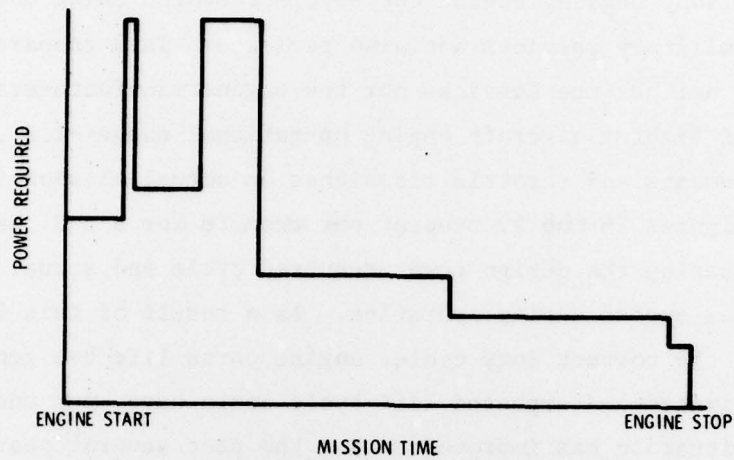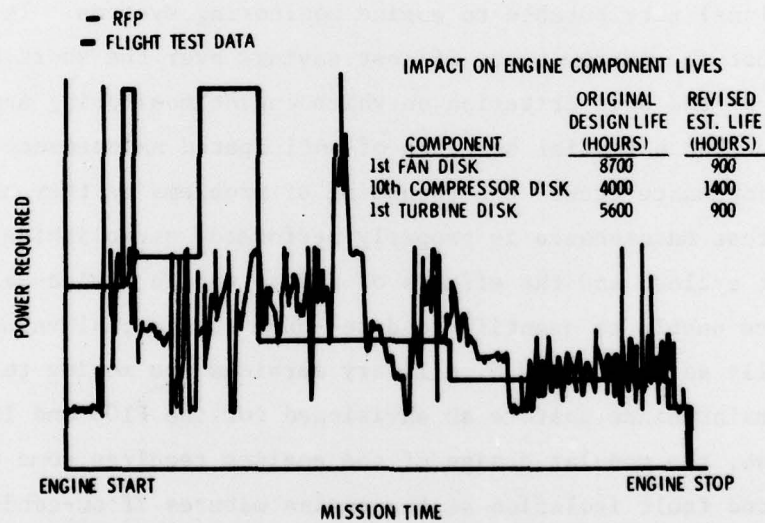
Fig. 16--F-14 proposed power required profile

Fig. 17--F-14 actual power required profile

Source of Figs. 16 and 17 is Ref. 5.

different mission profiles and each application should be tested to
its relevant duty cycles. Such information should help the services
in maturing existing engines during component improvement programs, as
well as in feedback to future engine design programs, especially now
that reliability, durability, and cost issues are apparently on an
equal footing with performance. Future aircraft turbine engine life-
cycle analyses should benefit immeasurably from the availability of
such information and detailed data.

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